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ABSTRACT

Current research and evaluation studies describe changing knowledge about the effects and conditions of computer-based tools in learning and teaching in elementary and secondary school classrooms. Current studies of computer-based tool use are characterized by: (1) a focus on many dimensions of learning, learners, and learning environments; (2) an increasing concern for learners' individual needs; (3) an interest in the process as well as the outcomes; (4) a concern for the effects of knowledge representation on learning and understanding; (5) interest in teachers' roles; (6) a focus on collaborative learning; and (7) a concern for evaluation methods. While tools are most often used to support the writing process, other applications include social studies problem solving; mathematics concept formation and problem solving; modelling of physical, biological, and social systems; graphing; science collaboration through the use of networking tools; and databases to support scientific inquiry. Recommended areas for research and development include learning and teaching using computer-based tools, reassessment to facilitate the integration of tools into the curriculum, evaluation methods, teacher preparation and enhancement, the development and application of new technologies, and social issues. (90 references) (GL)

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RESEARCH AND EVALUATION TRENDS IN THE USES OF COMPUTER-BASED TOOLS FOR LEARNING AND TEACHING

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ABSTRACT

Use of computer-based tools to support the learning process is increasing rapidly in elementary and secondary school classrooms. The reasons for their use range from a straightforward desire to expose children to the tools of the information age, to more ambitious goals of reforming the basic curriculum and pedagogy to make it more process-oriented and reflective of real-world complexity. This paper reports on our changing knowledge regarding the effects and conditions of tool uses of computers in learning and teaching as reflected in current research and evaluation studies. We identify strategic areas for research, development and evaluation.

INTRODUCTION

Tool applications are the fastest-growing genre of computer application to instruction in elementary and secondary schools. Yet we are just beginning to understanding whether or how which tools may help which students under what conditions.

The purposes of this paper are to: 1) define and summarize the current state of the art of tool applications of computers for learning and teaching in elementary and secondary education; and 2) suggest strategic areas for research, development and evaluation of such uses.

CHARACTERISTICS OF TOOL APPLICATIONS TO LEARNING AND TEACHING

A computer-based tool is a program a person uses to perform or facilitate an intellectual task, analogous to the way one uses a screwdriver or hammer to facilitate a physical or mechanical task. Key characteristics of a *tool* are:

- it is under the control of the person performing the task;
- it can be used to accomplish a variety of goals and tasks for a variety of purposes;
- the user determines the goals and purposes of the task at hand;
- the skills and intentions of the user determine the quality and nature of the process and product.

These characteristics distinguish uses of computer-based tools for learning from use of the computer as a teaching machine or object of study.

Why Tools Are Used: Pedagogical Philosophy

Tools are usually used to support process-oriented learning including inquiry, writing, problem-solving, decision making, collaboration, and other applications of higher-order thinking skills. They are also used to support concept learning and to provide access to information and algorithms.

Although educators have many reasons for providing tools as part of learning environments, there are certain themes of pedagogical philosophy that underlie much of the work with tools (e.g. see Nickerson [103]; Burton [22]; Papert [105]; Tucker [129]; Patterson & Smith [108]). These themes include:

- Constructivism. The learner is viewed as an active constructor of knowledge. The learner is not an empty vessel into which knowledge is poured; rather, the learner must be active and must be relating new information to existing knowledge (e.g. Hunter, [65], [67]).

- Conceptual understanding. It is believed inappropriate to have students learn procedures by rote. The concepts underlying procedures must be taught or discovered if the student is to be able to apply procedures to situations beyond those taught. (Brown *et al.* [16]; Brown *et al.* [18]).

- Self monitoring and self management of learning. Learners are viewed as taking responsibility for their own thinking and learning activities. This implies the need for metacognitive skills such as planning, directing attention, assessing their own comprehension and controlling anxiety.

- Lifelong learning. Education must be an ongoing process throughout life, not something acquired in school and later applied.

Use of Tools is Growing Rapidly

As more teachers become computer literate and more appropriate software tools become available, the tool use of computers in learning and teaching is growing rapidly. Many articles and books on the subject of using tools have been published recently (e.g. Canning *et al.* [24]; Hodges [58]; Hunter [62], [63]; Lockheed & Mandinach [77]; Sopp [120]; MicroSIFT [5], [132]). The State of North Carolina developed data bases on counties in their state to support the junior high course on North Carolina history, and distributed them to all 8th grade teachers in the state [104]. Teachers in school districts throughout the country developed data files and learning activities to support social studies curricula (e.g. [95]; [35]; [136]; [53]; [23]; [122]). During the past three years, approximately thirty data base packages to support the elementary and secondary school social studies curriculum were published by educational publishers. The Johns Hopkins

University 1985 national survey of instructional uses of computers asked the primary computer-using teachers which one of three major uses of computers seemed best at the time their school got its first computer and which one seemed best in 1985. The computer as a tool of the learner started as a small percentage of the priority of computer using teachers, but it is growing rapidly in importance relative to the two other uses shown [7].

In a survey, Talmis [123] found the largest percentage of their school respondents (27%) expected the use of the computer as a tool for students to use in writing and analyzing data to increase more rapidly than other uses. Schools with five years or more of computer-using experience are more likely to select tool use than are schools new to computing. Although the most frequent type of software *owned* by the schools was CAI drills and tutorials, the most frequently *used* programs were tools.

Research on tool uses has been supported for several years by Apple Computer [12], the National Science Foundation and other funding agencies.

NATURE OF CURRENT STUDIES OF TOOL USES

Current research and evaluation in this field is diverse, reflecting the wide variety of tools and purposes for their use. However, certain general characteristics distinguish this genre of research from earlier work with computer-assisted instruction.

The Research Focuses on Many Dimensions of Learning, Learners, and Learning Environments

Current research and evaluation in tool use seeks deeper understanding of the complex interaction of children, tools, and classroom learning environments. Earlier research in educational computing typically asked questions like "Does the computer make a difference in learning x?" Current tool researchers seek to be more sensitive to the multidimensional nature of learning processes, learning outcomes and learning environments. It is becoming more commonly understood that *technology is not an independent variable* -- that the ways in which a given tool are used depend on the cognitive, affective and social skills of learners as well as the social environment of the classroom, the school, and educational institutions (e.g. Michaels [88]).

Researchers Are Becoming More Interested in Individual Learners' Needs

Rather than asking group outcome questions, researchers are becoming more interested in the usefulness of particular tools or particular features of those tools, for particular learners. For example, Rosegrant [118] is interested in which features of the Talking TextWriter are used by children at various ages and developmental levels in their acquisition of literacy.

Tool Researchers are Interested in Processes as Well as Outcomes

Since tools are most often used to help in learning processes, the focus of the research and evaluation is correspondingly more process-oriented (e.g. Fisher [49]). For example, many studies of the role of word processors in writing are focused on the interaction of the tool with the nature of the writing process (e.g. Bruce, Michaels & Watson-Gregeo [19]; Daiute [33];). Similarly, the impact of the tools on science processes is of interest (e.g. Berger [8], [9], [10]). Many of the teachers and researchers working on tool uses are more interested in cognitive processes than in behavioral outcomes (e.g. Anderson *et al.* [2]; Barclay [4]; Collins & Gentner [30]; Dervin [34]; Fisher [49]; Hunter [65], [67], Malone [80]; Perkins [110], [111]; tum Suden & Rowe [131]).

Some Research Focuses on the Effects of Knowledge Representation on Learning and Understanding

Tool researchers are interested in interactions between learner and ways in which knowledge is represented by the tool. Thus the question is not simply "Is this tool effective in learning x?" but more subtly, "How does this particular characteristic of the knowledge representation help or hinder the learning process ?" (e.g. [47], [22], [2], [71]). For example, many studies are now being made of children's use and understanding of graphs in microcomputer-based laboratories (Brasell [14], [15];Linn *et al.* [8]; Mokros & Tinker [94]; McKenzie & Padilla [83]).

Some Research Focuses on Teachers' Roles

Teachers are inventing and creating new roles for themselves as they introduce new tools and processes into their classrooms (for example, more coaching and less lecturing). The roles of teachers are becoming an increasing focus of attention in our attempts to understand the uses of the tools in learning (e.g. Collins & Stevens [31]; Cohen et al [26]; Copeland [32]; Hawkins & Sheingold [57]).

Collaborative Learning is an Increasingly Important Focus

Relationships among learners using a tool are of increasing interest to researchers as well as teachers, partly because collaborative learning is often a major goal of the tool-using instructional innovation. Collaboration among students in small groups has been demonstrated to be a more effective mode of learning that either competitive or individualistic modes (e.g., Johnson, Johnson & Stanne [70]).

Evaluation Methods are a Major Concern

Often, tools are introduced to enable students to address more complex problems or concepts than they could without computer-based tools, or to focus on learning processes in new ways. A major concern then becomes how to assess these new learnings when existing tests and other assessment instruments were not designed for the educational purpose at hand. White [133], [134] and Parker [107], for example, spent a major part of their research efforts on the development of instruments to measure information processing skills. Layman & Kirkpatrick [72] devised a laboratory practicum to test students' microcomputer-based laboratory skills.

The Catch-22 of Tool Uses in the Existing Curriculum

Advocates of uses of computer-based tools in elementary

and secondary education face a seemingly unbreakable cycle of dilemmas. Use of the tool must support the existing curriculum and textbook if teachers are to adopt the innovation. But the existing curriculum and textbook were designed to meet the goals and needs of a paper-and-pencil print-oriented world. Hawkins & Sheingold [57] report on teachers' experiences in attempting to use general-purpose data management programs in science and social studies.

> Curricular issues were prominent in these two programs of research because we chose to study uses of the technology that had the promise of supporting skills of problem solving and critical inquiry. As such, the software did not have an obvious fit with the traditional curriculum. The curriculum had to be stretched or modified in some way to accommodate the technological functions...We were interested in how such stretching of the standard curricular vision, in the direction of higher-order problem solving skills that will likely be prominent in an information age, would be accommodated by today's classrooms [57].

EXAMPLES OF THE TOOLS AND STUDIES OF THEIR USES IN LEARNING AND TEACHING

The following tool applications and research on their uses are illustrative of current work in this field. Dozens of equally important efforts are not mentioned due to space limitations.

Tools Are Used Most Often to Support the Writing Process

The most commonly used computer-based tools in elementary and secondary education today (excluding programming languages) are used to support the writing process [28], [52], [138]. Word processors and related software are used in a wide variety of ways to support development of skills in the writing process -- from prewriting, to writing, to editing and publishing one's work. In 1985, among high school English teachers using computers, fully 69% indicated that students had improved their writing, editing or proofreading skill by using computers -- a greater consensus than for any other "effect" of using computers for any subject at any grade level. In addition, more business education teachers indicated improvements in student writing than indicated any other learning effect from computer use (21%). Overall 19% of all high school computers - using teachers suggested that improved writing was an important outcome of their use of computers, higher percentage than those using any other outcome.

Studies on using computers to help improve writing skills involve a wide variety of environments and evaluation criteria. After several years of experience, it is becoming more commonly understood that simply using the technology of word processors does not in and of itself improve writing skills of students or the teacher's ability to teach writing skills [81]. Daiute's book, *Writing and Computers* [33] examines the computer in writing instruction. She proposes that the introduction of the computer into the writing process changes the nature of the activity because it provides the writer with more power. In one study, Daiute concluded that the positive effects of computers on writing were attributable to recent changes in writing philosophy and approaches to using computers in education as much as they are related to the actual use of the computer itself. In a series of studies at the Interactive Technology Laboratory at UC San Diego, the computer was found to provide students with greater freedom to express their ideas by facilitating the invention, revision and publication of their compositions. Researchers have examined effects on student writing and editing resulting from functional learning environments (e.g. developing a newswire service or communicating via computer networks). These studies indicate that the development of functional writing environments, which contextualize students' learning activities in the classroom, improve the quality of students' writing. (Cohen & Riel [27]; Riel [113], [114]).

Other studies have focused on differences among students in their uses of the computer in writing. One study [137] concluded that poor writers made editing changes in their writing only at the word level, whereas better writers considered the overall effect of their document, inserting and deleting large segments of text before searching individual sentences for word-level errors. Morocco [96] observed that in remedial settings teachers overemphasized the editing capabilities of word processing software, interrupting the writing process too soon for editing.

Specially designed tools for children support the full range of the writing process. The QUILL project, for example, addresses six main goals [119]:

- Help children develop skills in planning and critical thinking.
- Integrate reading and writing.
- Make writing public.
- Support communication with real audiences.
- Encourage writing with and for peers.
- Facilitate revision.

Each goal is supported by a set of tools such as note takers and an electronic messaging system. In their research with children using these tools in classrooms, investigators found that the tools alone do not account for the most important changes which take place. Rather, modifications in the social organization of the classroom, changing roles of teachers and students and changing attitudes towards learning are all central mediating factors of computers' effects [20], [119]. Conversely, in a two-year ethnographic study of the use of Quill in two sixth-grade classrooms, Michaels found that the social organzation of the classroom shaped the nature of the tool and its uses. For example there was no use of the tools for writing across the curriculam in these classrooms because those were not a part of the teacher's normal classroom management and teaching style. The tool was used simply as a typewriter to type final manuscripts after they had been handwritten and hand edited on paper. Similarly, although the tool had been designed to encourage student-initiated writing, it was not used in that manner because the teachers assigned all the writing tasks and topics.

The "Talking TextWriter" is a computer program that combines word processing with synthesized speech, enabling young learners to use the computer as a tool to acquire beginning literacy. Teresa Rosegrant, designer of the

program, has studied the use of Talking TextWriter with children of various ages, under a variety of conditions [115], [116], [117], [118]. She found significant differences in the quantity of writing, strategies for revising, and quality of writing products for children using the speech output in comparison with children not using speech output. She has studied the specific ways in which children at different developmental levels use particular features of the tool, and has documented the characteristics of adult behavior in the tool environment which are most conducive to the children's development of literacy.

The use of word processors in the writing and language arts classroom is generating new phenomena and issues. For example, there is more collaboration between teacher and student and among students. This creates new questions about how to evaluate individual students' work. Another effect is the loss of an audit trail through one's revisions unless one consciously stores each version during the process. Thus teachers and students lose opportunity to reflect upon the process of revision.

Tools Support Social Studies Inquiry and Problem Solving

Data bases, data analysis tools, and simulations are highly appropriate tools in support of the social studies ([66], [21], [24], [43], [46], [58], [60], [61], [67], [102]). They are used for a wide variety of instructional purposes in a wide variety of ways--inquiry, problem solving, analyzing and predicting trends and relationships, forming and testing hypotheses, developing inductive and deductive logic, applying research skills, applying social participation skills, and providing access to specialized collections of information.

Dozens of curriculum materials packages supporting data base use in the social studies have been published, both by commercial publishers and regional education consortia. A few formal studies have been made of the ways in which such materials are useful in meeting the social studies objectives (e.g. White [133], [134]; Parker [107]). A difficulty in performing controlled studies of this type is the lack of suitable instruments and methods for measuring either process or learning outcomes.

The Bill of Rights unit of *The U.S. Constitution Then and Now* package [51] provides students with an opportunity to play active, creative roles in analyzing important contemporary cases involving the Bill of Rights. Assuming roles as investigators, students work in much the same way attorneys and paralegals work, using data bases to locate and organize precedent court cases that will support their position on cases. Instructional objectives for the unit include research skills such as analyzing documents for relevance to an issue or position, and social skills such as participating in persuading and negotiating in resolution of conflicts.

Tools Support Math Concept Formation and Problem Solving

Spreadsheet programs are sometimes used in applied mathematics classes to enable students to focus on higher level aspects of problem solving while the computer performs the computations. Programs to graph functions enable teachers and students to view many and varied examples of functions and their graphic representations, thus aiding intuition concerning the functions. Computer algebra programs such as muMATH [42] can perform complex algebraic manipulations usually taught by rote memorization of algorithms. Such programs are believed to free students to concentrate on more important conceptual issues, such as problem formation, problem solving, and evaluation of problem solutions.

A mathematical microworld is a system composed of objects, relationships among objects, and operations that transform objects and relationships (Thompson [125]). An example is the "Geometric Supposer." It allows students to conjecture about geometric relationships, to construct those relationships, examine them in a graphic environment, and reach conclusions supported by the tool-generated evidence. In his research with students using the mathematical microworld MOTIONS, Thompson [125] found that such tools can effect significant improvements in students' mathematical understandings and abilities [124], [126]. He finds that most students benefit from using mathematical microworlds by exploring them systematically, such as by controlling variables while manipulating others, and by using visual feedback to debug faulty understandings whenever they lead to unexpected results. However, he finds a significant minority of students are effectively blocked from taking advantage of the tool if they fail to understand the initial concepts depicted by a microworld, do not know how to explore ideas, and/or do not know how to generalize from examples

Modelling Tools and Environments Support Complex Problem Solving

Using modelling environments such as STELLA, curriculum developers can set up models for students to investigate, or students can create their own models to represent problems. Such models of complex, real-world physical, biological and social systems involve solving coupled, nonlinear differential equations. Before students know the formalism of calculus or the algebra of derivatives and integrals, they explore the underlying concepts of change and accumulation which are at the heart of calculus. Bob Tinker at TERC and Nancy Roberts at Lesley College are developing prototype software and learning materials for students in grades 7-12 to work with complex systems [128].

Microcomputer Based Laboratories Aid in Scientific Inquiry

Microcomputer-based laboratories (MBL) directly link temperature, motion, sound or light-sensitive probes to a microcomputer. Data measuring changes in such parameters as pendulum oscillations or light intensity are collected and instantaneously displayed on the computer screen [127]. Students control how the data will be represented (such as a graph of changing parameter vs time, or a pictorial representation like a thermometer), length of experiment, and quantitative ranges over which data are represented. Such tools enable students to test and retest hypotheses as the experiments progress, rather than performing all data analysis long after the experiment is completed. Since the computer is performing the clerical work of recording and storing the data, students have more time to focus on the purpose of the experiment and the analysis and interpretation of the data.

Studies of Graphing Skills

The use of graphs as a central means of communication in MBL raises important questions, such as: "What are the prerequisite skills students need to accurately interpret the graphs? Does MBL facilitate the acquisition of these skills? " Several studies have been made of the impact of MBL on children's graphing skills (Mokros [90], [91], [92], [93]; Nachmias & Linn [97]; Linn [8], [73], [74], [76]; Layman & Kirkpatrick [72]; Stein *et al.* [121]; Mokros & Tinker [94]; Barclay [4]). The studies show that students do develop ability to interpret graphs in an MBL environment, and also that they are susceptible to a wide variety of misconceptions. One problem is their uncritical assumption that a graph accurately represents the physical phenomenon being studied, such as temperature, rather than being a function also of the equipment and software used (e.g. a probe may not be calibrated correctly). Other studies are beginning to look more closely at the particular features of the MBL interface that affect students' cognitive development. In a study with 93 high school physics students from rural schools in Florida, Brasell [14], [15] found that one class session with MBL produced significantly greater ability to interpret distance-time graphs (but not velocity-time graphs) than control groups. Most of the improvement was directly attributable to the real-time nature of the graphing output in MBL. This was demonstrated with a control group of students who used the MBL interface with a brief (seconds) delay inserted into the graphing interface. This control group did no better on the learning task than students who did not use MBL at all.

Microworlds Support Science Inquiry

Several versions of microworlds for exploring Newtonian mechanics have been developed. For example, the "ThinkerTools" microworld developed at BBN Laboratories is designed to help children understand the nature of scientific laws and how they are established. The children induce and evaluate the laws of Newtonian mechanics through experiments with visual representations of objects that respond to various forces. [135]. Researchers are just beginning to identify the features of such microworlds that contribute to their effectiveness—such factors as multiple representations fo concepts and information, dynamic feedback, learner control and motivation.

Networking Tools Facilitate Science Collaboration

Earth Lab is a prototype classroom microcomputer networking system for the study of geography in upper elementary and middle schools. Earth Lab is designed for collaborative science. Geography units engage students in scientific activities such as compiling and analyzing databases and keeping electronic laboratory journals [101].

Kids Network is a science learning environment in which students share data they have collected and analyzed, such as data on the acidity of their local rainfall, with students in their own class, other classes, and other schools. Bob Tinker expects 1,000 schools from several countries to be involved in Kids Network in the next 2 or 3 years [128].

Data-Based Laboratories Support Science Inquiry

Data bases serve as flexible laboratories for developing and testing hypotheses and analyzing data from laboratory experiments (McLeod & Hunter [84], [85], [86]). *Weather and Climate Laboratory* [87] is a data-based laboratory in which students develop and test hypotheses concerning relationships among variables that affect weather. For the Weather Unit, data on fifteen variables such as wind direction, dew point, sky cover and temperature are provided on disk for each three-hour reporting period for each day in two months, July and January, for one location. This fine-grained data base enables students to analyze local and short term changes in weather and develop concepts such as the relationship between precipitation and changes in wind direction. Some of the data are in spreadsheet files, so that students can insert their own formulas and manipulate the data mathematically. In the Climate unit, students use data from the National Weather Service on 77 locations throughout the U.S., selected to represent different latitude, longitude and proximity to landforms and bodies of water which affect climate. They work with 13 variables for each month for twelve months for each location. Concept papers and lab report templates for each experiment, are in word processing files. By the end of the unit, students are able to hypothesize what combination of variables will result in precipitation, and test their hypothesis against the data.

Tools Aid in Development of Information Processing Skills

The need for students to develop skills and understandings in the handling of information is becoming more widely appreciated [1], [67], [11]. Data bases and electronic encyclopedias are used to help students develop and apply information-handling skills. Instructional materials are available to teach such skills (e.g., [68], [69]). Krendl & Fredin [71] compared students' use of print encyclopedias versus electronic encyclopedias to prepare term papers. The researchers examined whether students' thinking processes, as represented in their term papers, differed as a function of the delivery medium. Papers written by students who used the electronic encyclopedia to gather information scored significantly higher on measures of both horizontal (broad and shallow) and vertical (narrow and deep) knowledge. Use of the electronic encyclopedia facilitated searching across content areas, using key words to move around in the system to conduct a horizontal search. The print encyclopedia, on the other hand, was expected to facilitate focusing on a narrow topic and researching it in depth, reading one complete entry after another. Results suggested that students' high levels of interest and motivation resulting from use of the electronic encyclopedia yielded significantly higher levels on both types of knowledge. Another study [133] investigated whether the manipulation of a computerized file management program contributed to positive gains in students' ability to locate, gather, organize and evaluate information. Participants included 14 secondary social studies teachers and 665 students. Computer-using students scored significantly higher on the information processing scale than the control students.

However, if students do not have the prerequisite information handling skills they cannot take advantage of the tools. In an observational study [41], eighth-graders used a videotext system to conduct electronic database searches. They found that students had limited skills. They mastered only the simplest videotext commands and did not improve their rate of error over time; had difficulty understanding the

concepts and vocabulary of the electronic menus; accessed only a small quantity of electronic text compared to their use of available print materials; were able to search by keyword; and required constant adult assistance to log on to the videotext service, learn command operations and store text on disk files. Several other observational studies of students' problems in using tools have been published (e.g. Hawkins & Kurland [55]; Freeman *et al.* [50]; Hawkins, Char & Freeman [54]; Lockheed *et al.* [78]; Michaels [89]).

Tools Support Collaborative Learning

Small group decision making and problem solving can be strongly supported by tools such as data bases and simulations. The student groups are given a problem or decision making assignment. They use the data base or simulation to help them refine their problem or create an hypothesis, test the hypothesis or decision, analyze the data, interpret the findings or results of the decision, and communicate these results orally or in writing. For example, the data base may be designed to support role-playing in an historical simulation. In the Constitutional Convention unit of *The U. S. Constitution Then and Now* [51] students work as members of state delegations to the Convention of 1787. Three data files (Delegates, States, and Voting) and 76 word processing files stored on AppleWorks support the teacher and students in several ways. They:

- provide information.
- provide tools for students to use in retrieving, analyzing and organizing information.
- provide tools for students to use in communicating ideas and information among each other.
- provide structure and guidance to help organize the role-playing process.
- enable the teacher to tailor the activities to his or her own objectives and resources
- provide a means for students to create meaningful products from their work

The small group collaboration mode of tool use enables students to develop and apply skills in small-group participation which are important goals in the social studies. The data files, if properly structured, provide not only data but also structure for the small group processes.

Metacognitive Skills: Computer Tools for Learning Through Reflection

A major value in solving problems occurs when students reflect on how they actually solved the problem and how the strategies they used might be improved. Computer-based tools can capture the processes by which a learner carries out a complex problem solving task. This "audit trail" can become a useful object of study for students who are trying to learn how to improve their performance on a task or how to monitor their own learning processes (Collins & Brown [29]). The tool software built into Algebraland [17] and the Geometry Tutor [2] provide two examples. As the student takes steps in solving the problem (solving an algebraic expression for a particular variable or constructing a geometry proof), the tool creates a diagram showing the solution states the student reached and the operators the student used to reach those states. At any given point in the process the learner can observe her prior efforts, reflect upon them, and attempt a different strategy. Without such aids, the student might flounder endlessly, without learning from the experience.

More Tools

There are many more tools than those mentioned here. For example, school use of online data bases is increasing rapidly ([3], [62], [79], [106], [109]). New tools are being developed as the technology becomes more powerful (e.g., [56], [139]). Although an amazing amount of work has been done in the past few years in providing such tools to children in school, we have barely begun to understand the implications of these intellectual assistants for the development and self-actualization of children.

NEEDS FOR RESEARCH AND DEVELOPMENT

In this section we address the needs for research, development and evaluation in the following strategic areas:

- research on learning and teaching
- curriculum reassessment and reform
- evaluation methods and instruments
- teacher preparation and enhancement
- development and application of technologies
- social issues

Research on Learning and Teaching Using the Tools

We need deeper understanding and better theories about how children think and learn in complex problem-solving situations. There are hundreds of questions, at many levels. Some examples: What are the effects of different knowledge representations on children's understanding? How do different tool interface features affect children with different learning styles? In what ways does the ability to manipulate information in the form of pictures, graphs, sound and motion as well as text affect the learner's ability to conceptualize in a given subject area? What misconceptions are introduced by the knowledge representation employed? What characteristics of the tools constrain or inhibit children's cognitive, social or affective development? At what stage in learning a skill or subject is a particular tool most helpful? What roles does or can the tool play in enhancing or diminishing or shaping the child's metacognitive abilities? What characteristics of the tools influence affective factors in problem solving? In what ways can the tools facilitate or inhibit collaborative learning? How much ambiguity in problem specification is useful at what stage in a child's development? What prerequisite skills are needed before the learner can productively take advantage of the tool? What misconceptions are introduced or reinforced by the design of the tool or its interface? What characteristics of a tool inhibit or enhance a learner's ability to transfer the skills to new situations? What instructional methods are effective in helping students effect the transfer and application of skills to new problem areas? What level and kind of adult functioning is eventually attained by children who begin at a young age using powerful tools to address complex problem solving tasks and are consistently provided such environments throughout their schooling?

At least some of this research needs to be performed within the context of the tools and learning environments

actually available to and used in schools, rather than being focussed solely on advanced technologies available only in research laboratories. A major need is for systematic, long-term ethnographic studies of classroom events and interactions.

Curriculum Reassessment

Attempts to integrate tools into the curriculum will have limited benefits unless curricula are reassessed and modified, both in goals and in classroom practice [64]. What skills, knowledge and values are needed in the information age, both within and across disciplines? Some efforts are being made in this direction, but much more needs to be done. The state of California, for example, has integrated critical thinking skills into each grade level curriculum in social studies. James Fey at the University of Maryland has been examining the implications of numeric, symbolic and graphic information processing capabilities on what students can and should learn in school mathematics [48]. Expert study groups in all disciplines have for years been calling for increased curriculum emphases on *processes:* formulating problems; locating, evaluating, analyzing, interpreting and synthesizing information; estimating reasonableness of solutions; iterating and refining; communicating problems, methods, findings and interpretations to others. (e.g. [13], [98], [99], [100]). Yet in practice the curriculum is still highly content oriented with oversimplified problems, lower level skills required of students, performance of rote procedures, and little room for creativity or individuality. Other school constraints such as 45-minute class periods mitigate against work on solving problems on meaningful complexity.

Evaluation Methods

Hand in hand with the need for curriculum reassessment is the need for new methods of 1) evaluating students' progress and diagnosing their individual needs for learning; and 2) evaluating the effects of technology-based tools and their characteristics on the learning process.

Students, teachers, school administrators and school districts are now evaluated on the basis of student scores on standardized tests. Given the influence of these test scores on school curricula, textbooks, classroom activities, teacher evaluation, student placement, and the like, we must ask whether the tasks students are asked to perform on these tests are representative of the kinds of tasks, skills and attitudes students need to be developing in the information age. The model of norm-based, paper and pencil tests with multiple choice answers is being called into question and needs to be reassessed in light of emerging process-oriented goals in education. Alternative methods and instruments need to be explored and tried out. Work has been done on so-called adaptive interactive testing, but these are mostly traditional paper and pencil tests administered online. Other models may be possible. For example, can mechanisms be built into the design of the learner's tools that will assist the learner in assessing his own progress or assist the teacher in assessing the learner's needs? Can computer-based assessment tools be built which provide the learner with a set of problems along with problem solving tools and data to manipulate, and observe the learner's processes of solution? Researchers at the Educational Testing Service (ETS) are beginning to explore these possibilities.

Teacher Preparation and Enhancement

Increasing attention is being paid to needs, issues and problems surrounding the teaching profession in general and the relationship of teachers to technology in particular. Recommendations for action were made as part of the Conference on Technology and Teacher Education at U.C. Berkeley last year [75]. Visionary proposals for the reform of the teaching profession and the preparation of teachers have been put forth (e.g. Carnegie Forum [25]; Holmes Group [59]). A variety of approaches need to be tried, and teachers must be empowered to take a lead role in creating and assessing these approaches [130]. High technology learning environments in which students are working creatively and collaboratively on complex problems using powerful tools and large amounts of information, are diverse places which no single model of "the teacher role" will fit. Many different models of classroom environment and teacher roles need to be experimented with and be observed by teacher educators, teachers and novice teachers. Creative and flexible approaches to state regulation of the teaching profession need to be studied and tried. Collaborative work among teachers within a school needs to be encouraged. For example, library/media specialists can work closely with a history teacher to plan and conduct learning activities in which students use online data bases as part of their research projects [62].

Development and Application of New Technologies

In this time of rapid technological advances, there is always a discrepancy between the capabilities of the machines already installed in schools and the capabilities of the machines available in the general economy. Educational software developers and publishers who depend on school purchases of their products are forced by the economic system to confine their development efforts to the installed base of machine capabilities in the schools. If new technology applications to elementary and secondary education are to be ready by the time they are needed and wanted by the schools, work must be initiated now. Nearly all the advanced technology work in instruction today is funded by and for the military. The National Science Foundation Science Education Directorate has a small (approximately $5 million) budget for the Advanced Technology program. This program funds a small number of highly innovative and risky projects which are expected to have a five to ten year time frame before any payoff is expected, and multi-year funding is a critical component. The program focuses on educational application of emerging technologies such as laser disc and computer-generated imagery in four strategic areas: knowledge based systems and intelligent tutors; computational tools and symbolic manipulation systems; authoring systems; and programming and problem solving. More support is needed for the design, development and evaluation of promising new technology tool applications specifically aimed at elementary and secondary education. These projects should have relatively long-term (5 to 10 years) development cycles. They should not be constrained by the installed base of equipment in the schools, but rather take advantage of the most advanced technology needed to try out the ideas.

 One development area that is just beginning to be

explored is the creation of interactive coaches or advisors that operate on top of or in conjunction with the tool [112]. These could assist students in planning, problem definition, critical thinking, reflecting on their strategies, and other skills which are difficult for the teacher to assist in at all times, without taking away from the learner control inherent in the tool philosophy. Such an approach combines the expertise of those involved in research on intelligent tutoring systems, cognitive task analysis, mental modelling, and tool-building.

Another promising area is educational applications of large multimedia data bases. Much experimentation needs to be done with such systems in the areas of interface, pedagogy, browsing and retrieval capabilities, classroom management, curriculum integration, relationship to textbooks. Work especially needs to be done in the area of knowledge representation and appropriate learner interface with various knowledge domains. This becomes more critical as large scale data bases on optical media become more affordable. Sophisticated tools such as hypertext software are becoming more readily available for use with large data bases, and open new opportunities for design of appropriate systems for students (e.g. Yankelovich [139]; McClintock [82]).

A third promising area for development of educational applications is the use of object-oriented languages such as SmallTalk and logic-oriented languages such as Prolog, as tools of the learner to create and experiment with their own microworlds (e.g. Ennals [43], [44], [45]; di Sessa [36], [37], [38], [39]; di Sessa & Abelson [40]).

Another important technology application is in the design of tools to support collaborative work. Local area networks and telecommunication networks can provide the hardware base for collaboration, but research and development is needed on software supports for collaboration among students, teachers, and "the outside world."

Social Issues

Myriad ethical and values issues are arising faster than our culture has been able to address them -- issues involving intellectual property rights, privacy, honesty in communication, equity of access to information, to list just a few. As the tools of the information age begin to pervade the learning environment of children, it becomes imperative that they be taught the ethical, legal, moral and social aspects of the uses of the tools. Much work is needed in understanding social issues involved in use of electronic technology; deriving from that understanding the implications for what students need to be learning and valuing; and integrating these requirements into teacher education, curriculum materials, and features of technology tools.

SUMMARY

A wide variety of computer-based tools are available to assist learners in all subject areas, and interest in the use of these tools in elementary and secondary schools in the U.S. is growing rapidly. Research on learning and teaching using such tools has barely begun. Many new and sometimes subtle questions are beginning to be asked about how children think and learn in the information-rich, complex problem solving environments made possible through the technology. Attempts to integrate use of the tools into the curriculum and current classroom practice will have limited benefit unless curricula are reassessed and modified to take into account the kinds of skills and knowledge needed in the information age. Hand in hand with the need for curriculum reassessment is the need for new methods of evaluating students' progress, diagnosing their individual needs for learning, and evaluating the effects of technology-based learning environments on the learning and teaching processes. High technology learning environments in which students are working creatively and collaboratively on complex problems using powerful tools and large amounts of information, are diverse places which no single model of "the teacher role" will fit. Many different models of classroom environment and teacher roles need to be experimented with, and teachers must be empowered to take a lead role in creating and assessing these approaches. Long term projects are needed to design, develop and evaluate promising new technology applications for elementary and secondary education.

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